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on

STUDIES OF PATTERN-PERCEIVING AND LEARNING NETWORKS

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Some features of a baby's sensorimotor development have been incorporated into a computer program. I have not tried to simulate the details of what a baby does. I am, rather, trying to learn what principles of operation one would look for in any kind of system, biological or otherwise, that can really be said to be perceiving and performing skilled actions. Like the work described in Section A, this study seeks new uses for the same elements which are being employed by many investigators.

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This study deals with problems arising in the work described in Section B. Most current rigorous mathematical work has concerned the circuit elements of sensorimotor control systems. The present study attempts to learn what functional organizations must be built out of these elements. I have found that recently developed mathematical concepts give a way of thinking rigorously about these problems of structure. This is a necessary condition for solving any of these problems.

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I. Summary of Research During the Past Year

A. Networks for Selecting Patterned Inputs and Outputs

(a) Purpose

A great number of studies have been devoted to networks possessing a few of the many properties of neural networks. For example, many studies have dealt with the switching properties of elements with all-or-none response. Many other studies have dealt, on the other hand, with the transmission of continuously varying excitation produced by the interaction of elements capable of graded responses. These, too, may serve as switching networks by the addition of thresholds. Both these aspects of networks have been widely studied in regard to their usefulness in tasks requiring pattern recognition and learning.

It is common to say that since learning means connecting stimuli with behavioral responses, one might look for development of corresponding physical connections between elements of the network, for instance, changes in synaptic conductivities, or connection strengths in general. These changes might cause the network always to respond to a particular stimulus with the activation of a circuit which produced a particular response, rather than with a different circuit which produced a different response. This is a very useful approach, but there may be other approaches which are sometimes advantageous.

Another approach has been investigated under the contract. A list of desirable behavioral properties of the system suggested designing the networks so that their resonant modes constituted the desired input or output patterns. These behavioral properties followed directly from such a model, while they would require special mechanisms under the approach described in the preceding paragraph. An example of such a property is that the resonant network could easily select a pattern of activity of certain output elements, while rejecting a different pattern of activity of exactly the same elements. In fact, the resonant networks for producing patterned outputs need not consist of separate circuits with a selector mechanism, but may have a single circuit which at different times produces different patterns.

(b) Progress

In order to investigate the feasibility of this approcah, the general equations which would have to be satisfied by such a system were presented, and specific examples of a patterned output selector were studied numerically. It was found that infinitely many linear systems would suffice (references (1) and (2)). Next, it seemed useful to inquire whether such systems could easily be realized by simple circuit elements. As an example of a useful circuit element, the two-factor linear model neural element of Prof. N. Rashevsky was considered (references (1) and (3)), and it was demonstrated that infinitely many networks of these elements could realize any of the infinitely many resonant systems corresponding to the desired patterns. Two-factor networks were designed for the specific numerical example. Finally, the question was raised whether it would be possible to obtain desired resonant modes in an aggregate of networks by selecting and improving those networks which exhibited almost the desired behavior, and some formulas were derived for the modification of networks (unpublished).

(c) Publications

1. Greene, P. H. "On the representation of information by neural net models," In Self-Organizing Systems 1962, edited by M. C. Yovits, G. T. Jacobi, and G. D. Goldstein, Washington D.C.: Spartan Books.

2. Greene, P. H. "On looking for neural networks and 'cell-assemblies' that underlie behavior. I. A mathematical model." Bulletin of Mathematical Biophysics, 24 (1962): 247-275.

3. Greene, P. H. "On looking for neural networks and 'cell-assemblies' that underlie behavior. II. Neural realization of the mathematical model." Ibid., 395-411.

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B. Computer Model of Sensorimotor Development

(a) Purpose

In order to study the structure and acquisition of perception and motor skills, some features of a baby's sensorimotor development have been incorporated into a program for the Philco 2000 at System Development Corporation in Santa Monica. The Artificial Intelligence Division of the Research Directorate at SDC has kindly provided the services of a programmer, Mr. Terrence Ruggles, and all the machine time we could use, without charge.

We have not tried to simulate in any realistic way the details of what a baby does, for this is not our purpose. We are, rather, trying to learn what principles of operation one would look for in any kind of system, biological or otherwise, that can really be said to be perceiving and performing skilled actions. A baby is a very good example of such a system, and we are trying to model the principles by which he operates, rather than the precise appearances of the ways in which he applies them. For instance, the baby performs purposeful actions, naturally described in terms of their effects on his environment, rather than in terms of particular muscle movements, which might have been any of a number of entirely different movements accomplishing the same purpose. We are trying to learn more about the sequence of development which can bring about this purposive regulation of movements.

There have been a number of different approaches to problems like these. One is to deal with elements at the neural network level, adjusting connection strengths or thresholds, while another is to write computer programs in which symbols may designate complex behavioral acts. We are working somewhere between these levels. We wish to identify the structures which the networks are intended to produce, in order to give meaning to the choice of network processes, just as in studying a painting, we desire knowledge at the level of perspective, composition, and style to give meaning to the individual brush strokes. By working in between the two levels cited, we hope to learn how the structures can be brought into existence. We are, in computer terminology, trying to build a compiler for skilled actions. The intermediate level on which we work expresses itself in our choice to compile actions neither in "machine-languages" of individual nerve impulses, nor in terms of elaborate subroutines, regarded as given, but in the behavioral counterpart of intermediate level symbolic languages: they have operations like "MULTIPLY AND STORE," and we have operations like "TURN HEAD BACK AND FORTH."

(b) Progress

The approach was based upon Jean Piaget's interpretation of sensorimotor development, outlined in the 1961 Annual Report under this contract. Since we did not feel that an attempt at a realistic simulation of the details of infant behavior would be instructive, we needed to work with a simple model which we hoped would retain some of the essential features in skeleton form. Such a model was suggested by the pattern recognizer of L. Uhr and C. Vossler ("A pattern recognition program that generates, evaluates, and adjusts its own operators," Proceedings of the 1961 Western Joint Computer Conference). Their program was given or evolved a collection of templates which it matched to stimulus patterns, and it weighted the templates according to their usefulness in distinguishing patterns. We considered Piaget's infant to be a collection of half a dozen or so Uhr-Vossler machines, generalized in various ways. A machine corresponds to each basic activity like moving the head, sucking, moving the arms, or grasping. The Uhr-Vossler templates are numerical patterns which are fitted to a stimulus object. Our patterns are numerical configurations describing movements or nerve or muscle excitations, and are adjusted to fit the environment.

So far, a substantial part of the "head movement machine" has been programmed. Each head movement consists of two parts, the movement itself, which, in our initial version, is simple, and the conditions for triggering it, which are more complicated, involving a number of special contingencies. Examples of our head patterns are a head-drifting-at-random pattern, a head-rapidly-back-and-forth pattern, a head-turning-in-one-direction pattern, and a sucking-when-head-is-touched-and-sometimes-otherwise pattern. We hope that a small number of patterns will be sufficient, recalling that all the instructions for a large general purpose computer are frequently printed on a small card.

Our components are turned on and off and interact through changes in excitation levels governed by the two-factor equations for central nervous activity developed by Professors N. Rashevsky and H. D. Landahl. For example, the intensity of a certain "sucking level" changes according to these equations as the lips pass back and forth past the nipple. When the sucking level reaches a threshold, sucking starts, but even before this, increase of this variable regulates the head movements, according to similar equations, so that the position of the mouth narrows down quickly to the nipple.

We are not interested in suckling as a physiological process. Reference 1 below explains how suckling movements and their later extensions are prototypes of acts which prolong perceptual activities, suppress disturbing influences, focus attention on meaningful objects, and enable skilled movements involving spatial relationships. Section 3 below outlines an attempt to develop a theory which will tell how this development might take place in any perceiving and acting system. It is only through such a theory that we shall know what additional mechanisms to put into the computer program, because we are studying sensorimotor development, not a gadget that does some one thing well. One interesting remark is that, contrary to the tacit assumption of many investigators, there is no essential division between sensory and motor systems in our program. In fact, the sensory system uses motor actions (or representations of them) in order to perceive. Our attempt to understand how this can be done is one illustration of our endeavor to look for and at new issues which must be faced even though we are using the same elements everyone uses.

(c) Publication

Greene, P. H. and T. Ruggles, "CHILD and SPOCK (Computer Having Intelligent Learning and Development; Simulated Procedure for Obtaining Common Knowledge)", invited paper, Bionics Symposium 1963, Dayton, Ohio, March, 1963.

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C. Mathematical Theory of Sensorimotor Organization and Perception

(a) Purpose

This project is aimed at precisely formulating ways of describing elements of sensorimotor structure at the behavioral level of actions, as distinguished from physiological processes or individual movements which must be organized into these actions. It deals with questions which arose in designing the computer model of development based upon Piaget's interpretations. Others have looked at these questions from many different points of view, but in all these approaches, the mathematically describable elements are far removed from the structural organization at the behavioral level. Such studies either tell about sub-behavioral events (e.g., path weightings, or synaptic changes), in which case one can only assert his faith that the behavioral items are somehow recoverable, given enough of the sub-behavioral events; or else they tell how often or how strongly behavioral items occur, but not what they are. Is there anything equally precise which can be said about the behavioral structures themselves, the acts as a whole? Recent progress indicates that the answer is yes: it is possible to formulate the questions mathematically in such a way as to reveal the existence of issues which could not even be perceived as issues previously.

The need for such a formulation is generally being overlooked in the torrent of papers appearing on the subjects of self-organization and artificial intelligence. I repeat that if one is describing the elements of composition, perspective, and style in a painting, descriptions of juxtapositions of individual dots of paint become meaningful only insofar as they can be stated in terms of concepts at the compositional level. Similarly, in understanding skilful human or machine behavior, the rules for connection strengths and the like between individual elements have meaning only in relation to the behavioral structures which are to be achieved. All current research efforts on logical networks, synaptic strengths, and so on, are, like any form of circuit theory, indispensable tools when you want to build something - but first you must know what you want to build.

(b) Progress

The first half of the present contractual year was devoted to identifying the behavioral structures which should be studied, and looking for conceptual tools with which to do so. The problems just did not seem to be the kind mirrored by the problems of logic, information theory, reinforcement theory, and other common approaches. (Of course, these disciplines would be most valuable in studying other aspects of the same systems I am studying.) It turned out that certain concepts of "fiber spaces" with "structure sheaves" provided the first relevant mathematics I had ever seen. These will not be explained here, but certain qualitative ideas will be presented.

As explained in the previous section, the system is considered to be in part a collection of devices which when activated run through their repertoires of acts, which have to be modified and coordinated through learning. The system is supposed able to remember a few relatively undifferentiated movements which work well in some particular circumstance, and not so badly within a range of related circumstances. The basic problem is to piece together these partial acts, defined on overlapping ranges of circumstances, into an integrated act which could be performed in a wide range of circumstances, and which might utilize any of a number of partial acts, all harmoniously adjusted. This procedure must be revised as more highly differentiated movements and discriminations of ranges of circumstances become possible. These ideas, when interpreted in some simple cases, were found to be aptly stated in terms of ways to adjoin structures defined on successively refined coverings of a manifold. Along with this notion of a basic function of the control system came an awareness of issues concerning organization which could not have been perceived before. They came from the wide range of mathematical associations which cluster about the ideas which have just been mentioned. These mathematical issues directly involve the behavioral level, rather than the sub-behavioral, and the structural, rather than the enumerative, aspects of behavior.

The trick is to look directly at acts and see mathematical structure. For example, the physiologist may look at a mapping between psysiological parameters and the position of the hand. But at the behavioral level we may be interested to know about the act of picking up a pencil, and we need to find mappings between physiological parameters and the position of the hand relative to the pencil. However, the pencil could be in any position, and we would come up with the right muscle movements. Hence, we do not have just one mapping, but a bundle of related mappings defined over a manifold of possible positions of the pencil (or of possible physiological configurations). The physiologist is studying single slices of this bundle, but it is possible to name specific elements of bundle structure which can be seen behaviorally (if one knows the concepts which tell what to look for), but not physiologically. This is important because fitting the next act to be performed with the pencil to the act of picking it up establishes a mapping between bundles and not just slices, and the bundle structure imposes conditions on these mappings.

In general, then, the mathematical relations hold among structures which cannot be "photographed" - in the above example, between structures involving a range of things the system could potentially do in a range of different circumstances, rather than between the things one sees it do before one's eyes. The fact that it takes practice to grasp the mathematical ideas well enough to reason with them shows how much theoretical preparation is necessary before one knows what to look at in the laboratory. Since the mathematical ideas cannot be explained here, a different example will have to illustrate the point that the significant relations hold between structures which cannot be seen. The hand and arm can move anywhere, and the eye can look anywhere: what more is there to say about behavioral structure? But look instead at a typical behavioral task: learning coordination by moving the hand while keeping vision focussed upon it. We may think of the line of sight as a rigid rod pivoted at the eyeball and extending out into space. The arm and hand become part of a linkage having in effect a slider at the hand, which slides along the rod. The lengths of the links are determined by body dimensions and depth of focus. We have, in effect, the kinematic equivalent of a five-bar linkage, about which much can be said mathematically, whereas all that can be photographed is freely moving bars which can be in any position whatever.

Consider the kinematic example just mentioned. The fact that we can hold a pencil in our mouth or between our toes and produce our normal handwriting the very first time shows that during development all sorts of correlations between different kinematic mechanisms had to be learned. Suppose that this was done, as suggested, by piecing together partial acts. Behaviorally, we do not care which of these partial acts is being used at a particular point of the overall action. Any partial act that works for the purpose is as good as any other, so long as it is arranged that by the time the system has left the region within which the chosen act fits the purpose, the system has switched to any one of the class of partial acts which fit the purpose in the new region. Thus, from a behavioral point of view we might sometimes wish to find relations holding, not between the "photographable" movements, but between equivalence classes in which we consider two movements equivalent if they agree in effect on any neighborhood, however small, of a point. These classes are called germs of the mappings constituting the movements. We are also interested in similarly defined germs of transformations measuring the differences between various ways of fastening together the partial acts into overall acts.

As development progresses and the regions become more highly differentiated, one builds up more complicated and refined versions of the above structures. At this more refined stage, the meaningful relations between two small details of the movements of two kinematic mechanisms which must be coordinated arise only insofar as they may be traced back to their common less differentiated precursors which sketch the broad outlines of the movements. One can show that it is too much to expect a reasonable system to trace these structures back in any unique way. However, it is possible to show (by a mathematical argument in which one considers functions from an abstract topological structure which describes the pattern of intersections of the partial regions, to sets of the above-mentioned germs of mappings) that the result of certain ways of tracing back to precursors is well defined, no matter how the system does it. This example shows that it is possible to formulate issues to be faced and arrive at conclusions which could not have been perceived without the theory.

In summary, it may be said that these ideas have been developed to the point that it is clear that the issues <u>are</u> involved in sensorimotor coordination, but it is not yet clear whether I shall be able to derive the useful conclusions that I am sure someone will. In fact, it is only recently that I have become able to understand the ideas well enough to hold them all at once in my mind to reason about them. If these issues are as relevant as I suppose, then understanding them is like knowing calculus if you want to be an electrical engineer: with it there is no guarantee that you will discover anything, but without it you can't even get started trying. In other words, up to a short time ago I feel that I could not even think about the problems, let alone try to solve them. During the coming year I plan to try to do something useful with the ideas.

II. Proposed Plan of Research

A. Networks for Selecting Patterned Inputs and Outputs

I plan to continue with the study of how to improve the behavior of a network that is doing almost the desired thing.

The infinity of networks with the same resonant behavior will differ in steady-state response and in response at frequencies other than the resonant frequencies. I plan to investigate whether it is possible for a system to select in a natural way resonant nets satisfying some condition on the steady-state and frequency responses. Of course this is possible mathematically, but I wonder whether it can be done in a natural, self-organizing way.

I plan to study the equations already obtained, and others like them, on an analogue computer which is soon to be installed at the University. First of all, I want to get a general feel for the solutions, for example: How precisely must the parameters be specified? How sharp are the resonances? What do superpositions of patterns look like? Is it really easy to select useful patterns this way, or does it just look good on paper? Is it possible to improve networks in a simple way?

B. Computer Model of Sensorimotor Development

I plan to finish up the straightforward parts of what Piaget calls Stage I, the use of reflexes. One of the main things to add to the present "head machine" is vision. The spatial mechanisms of vision and prehension will require messy mathematics of kinematics.

Once I have these mechanisms, I still will not be satisfied, for the point is to understand the possibility of growth of abilities, not how to do one particular thing. In conjunction with the development of the theoretical ideas (section C), I plan to study how a control system can cause any of a set of kinematically dissimilar mechanisms to perform the "same" act. The first step will be to see what the computer needs to correlate the movements of two different effector mechanisms, subject to the requirement that it never will be allowed to make computations or keep elaborate tables of data. My hunch is that this would not be possible for something like hand movements alone, but that somehow it is made possible by using a hierarchical structure involving the rudimentary spatial relationships built up through such actions as suckling, as mentioned above. I am beginning to get an idea what to look for theoretically to understand this, and that will be the subject of study referred to below.

C. Mathematical Theory of Sensorimotor Organization

I plan to investigate the ways in which partial acts are pieced together into a total act by means of the notions of fiber spaces. For instance, one part of learning a motor skill is to take apart pieces of other acts and put them together again in a different way to form a new act. The study of the ways in which the pieces can be "glued" together to form spaces locally isomorphic to the original spaces is one of the things most naturally done using the techniques I have mentioned.

The immediate application of such ideas is that they tell what structure has to be represented in the computer program of Section B in order for it to perform the same acts with different effector mechanisms. At the very least, these techniques give a way of systematically setting down the necessary elements of information. I plan to use this systematization in getting the computer to correlate the workings of two different mechanisms, as proposed in Section B. In effect, I shall be getting the computer to embody the abstract structures of these fiber spaces.

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